THE METEOROID HAZARD TO THE APOLLO SPACECRAFT

April 30, 1964

B. T. Howard
G. T. Orrok

Bellcomm, Inc.
Washington, D. C.

TABLE OF CONTENTS

LETTER OF SUMMARY AND RECOMMENDATIONS

* * * * *

		Page
1.0	INTRODUCTION	1
2.0	COMMENTARY ON BLOCK II STUDY	2
2.1	The Meteoroid Environment	2
2.2	Penetration Mechanics	4
2.3	Failure Modes	8
2.4	Reliability Goals	10
2.5	Recommended Actions	13
3.0	FUTURE PROGRAM	17
3.1	Meteoroid Environment	17
3.2	Penetration Mechanics	18
4.0	CONCLUSIONS	20

APPENDIX A

APPENDIX B

FIGURES

REFERENCES

DISTRIBUTION

April 30, 1964

TO: J. F. Shea, NASA-MSC

FROM: B. T. Howard, Bellcomm

SUBJECT: Analysis of the Meteoroid Hazard to the Apollo Spacecraft

This letter presents a summary of the conclusions and recommendations made as a result of a review, conducted in conjunction with the Flight Technology Branch of ASPO, MSC, of the meteoroid hazard to the Apollo spacecraft. A more complete discussion of the various problems is presented in the attached report.

I. Comments on the Block II C/SM Meteoroid Study

(1) The meteoroid environmental model utilized in the Block II study is supported and believed to be adequate for the study. The model is believed to lead to conservative results and to be subject to an "engineering uncertainty" of $10^{\pm 1.1}$ in probability of penetration for a given spacecraft wall.

(2) The models used for penetration mechanics are believed to be reasonable for the purposes of the study but inadequate for design. The bumper factors utilized are, in general, conservative but underestimate the relative effectiveness of a well designed bumper compared with that of less optimized multiple walls. The models used lead to an overall uncertainty of $10^{\pm 2}$ in penetration probability or, with the realization of good bumper design, $10^{+0,-2}$.

(3) No extensive study of failure modes was performed but the following comments may be made:

(a) The failure modes of multiple walls by impulsive loading, spallation, and penetration by low velocity fragments is only qualitatively understood. Consequently definitive study of the failure modes of spacecraft components is not possible.

(b) The assumption that pressurized fuel tanks will rupture on impact is obviously conservative but was nevertheless supported when qualified opinions were sought. It is believed that less conservative assumptions would result from an experimental program.

(c) The assumption that complete penetration of the heat shield is permissible is supported but some uncertainties remain concerning extensive fracture on impact at low temperatures.

The overall result of the assumptions used for failure modes is to lead to indeterminate conservatism.

II. The following recommendations are made:

(1) Both major spacecraft contractors (NAA and GAEC) should be instructed to include the hazard due to the meteoroid environment in their reliability/weight budget and to take any necessary design actions.

(2) The following specific recommendations for design actions are made from meteoroid considerations alone:

(a) Command Module: no action is necessary.

(b) Service Module: a meteoroid bumper of 0.01" aluminum should be added, separated from the present spacecraft skin by a 1" layer of foam. The weight of such a bumper would be 70 lbs with 140 lbs of foam leading to a total weight of 210 lbs.

(c) Lunar Excursion Module: the 0.006" aluminum thermal shield of the LEM should be utilized as a meteoroid bumper. Where necessary, a second skin should be added at least 2" behind the thermal shield to raise the thickness of the inner skin to at least 0.012" on the descent stage and at least 0.018" on the ascent stage. Such action would lead to a weight penalty of 62 lbs on the ascent stage and 40 lbs on the descent stage for a total of 102 lbs.

(3) A summary of the calculated performance with respect to meteoroid hazard following the actions indicated above is given in the table below.

Spacecraft Subsystem	Crew Safety Probability	Mission Success Probability
CM	0.9997	0.9997
SM	0.9997	0.9997
LEM (Ascent)	0.997	0.992
LEM (Descent)	0.998	0.965
Total	0.995	0.957

It is recommended that these probability values, calculated on the basis of the Block II study models, be regarded as acceptable (it is noted that somewhat less weight applied to the LEM gives a crew safety probability of 0.99986 if a possible bumper model, discussed in the attached report, is used).

III. Suggestions for Future Actions

(1) Meteoroid environment

(a) Support for the Harvard Radar Meteoroid Project should be continued. Every effort should be made to encourage prompt analysis of the data obtained.

(b) Every effort should be made to obtain some minimum modification to the SA-10 spacecraft to allow some form of bumper structure to be flown. If this is not possible, thicker sheets of aluminum (up to 0.25") should be used.

(2) Penetration mechanics

(a) Better understanding, both theoretical and experimental, should be obtained concerning meteoroid bumper design. A proposal, submitted by GM to the Structures Division, MSC, is regarded as technically excellent.

(b) Better empirical information concerning the more complex structures in the Apollo spacecraft is required. A complete integrated program could, perhaps, be carried out by MSC in conjunction with ARC.

(3) Failure modes

(a) Close contact should be maintained with the experimental studies on the failure of pressurized fuel tanks which are in progress at LeRC and Boeing. Full scale, or simulated, proof tests of the SM tanks should be required as part of the development program.

(b) The major spacecraft contractors should be instructed to perform a continuing, careful, documented review of the failure modes and sensitivities of the spacecraft components as a result of both primary impact and secondary impact by spall, spray or solid fragments.

It should be stressed that these comments and recommendations are made as the result of a joint study with ASPO, MSC, and that they should be considered together with the results of other parts of the Block II C/SM meteoroid study presented elsewhere.

B. T. Howard

Att: The Meteoroid Hazard to the Apollo Spacecraft

The Meteoroid Hazard to the Apollo Spacecraft

1.0 INTRODUCTION

This report summarizes the results of a review of the hazard offered to the Apollo spacecraft by the meteoroid environment conducted in conjunction with the Flight Technology Branch of ASPO, MSC. The review has involved discussions with the major spacecraft contractors (NAA and GAEC), NASA centers (MSC, ARC), and certain industrial organizations (GM, ADL).

The prime objective of this review was to cooperate with the Flight Technology Branch in determining the manner and extent to which the meteoroid environment should be included in the design requirements for the Block II Command and Service Modules. The results of the Block II meteoroid study will not be presented in this report, which will be restricted to:

(1) A commentary on the Block II study primarily concerned with the uncertainties in the assumptions made during the study and the effects of these uncertainties on the study results.

(2) A discussion of some recommended future actions for the reduction of these uncertainties.

(3) In appendices,
   (a) The presentation of a tentative model for meteoroid bumper design, and
   (b) discussion of the particular problems of the major spacecraft subsystems.

2.0 COMMENTARY ON BLOCK II STUDY

2.1 The Meteoroid Environment

The model environment used in the study is summarized in Table I below.

TABLE I

Sporadic flux: $\log N = 18.2 - 1.34 \log m + 2.68 \log \left(\frac{440}{\rho_p} \right)$

M.K.S. units

Mass of 0th magnitude meteoroid: 1 gm

Meteoroid density: 0.5 gm cm^{-3} Velocity: 30 km sec^{-1}

Shower flux: to be neglected

Lunar secondary ejecta: compensated for by ignoring shielding effect of lunar surface

The sporadic flux relationship is that of Whipple[1], and represents an attempt to combine data from all sources, but is primarily based on visual meteor observations. The flux ranges of interest to the Apollo spacecraft are those observed by meteor radar programs where the data are more questionable. The errors due to uncertainties in mass normalization and in flux extrapolation are comparable in this range and lead, combined independently, to an uncertainty of about a factor of $10^{\pm 0.95}$ in probability of penetration for a wall designed for a given meteoroid mass*.

The uncertainties in density, structure, and velocity of the design meteoroid lead to further uncertainties when combined with hypervelocity penetration equations to evaluate particular structures. Cometary meteoroids are

* The numerical uncertainties quoted here are "engineering estimates", and do not have a rigorous statistical basis. They are roughly considered as 90% likely to include the "true" value.

described as fragile dustballs (i.e. aggregates of small particles of presumably higher density), and the errors due to using a low density homogeneous model are uncertain. Preliminary calculations at ARC suggest they may not be great, and it further seems likely that the assumption is conservative.

The velocities of sporadic visual meteors near earth are known to vary from 10 to 70 km sec^{-1}. The distribution of the radar meteors is ill defined. The use of an average velocity could lead to non-conservatism if reliance is placed on highly efficient bumpers but appears reasonable in the present study.

The neglect of meteoroid showers in spacecraft design is based on the postulate that the operational launch constraints offered by the occurrence of the larger showers are tolerable[2]. This postulate appears reasonable since the forbidden periods are short if an increase in flux of a factor of 2 is accepted. Since this factor is much less than the uncertainty in the sporadic flux model it is further reasonable that the latter remain unchanged. Lastly, it should be noted that there is evidence[3,4] that many prominent visual showers are vastly reduced in the flux range of interest to the spacecraft.

Lunar secondary ejecta do not affect the Block II C/SM design but have been considered in an associated LEM study. As discussed in Appendix II, secondary ejecta need only be considered if high efficiency bumpers are used for protection, and consequently the assumption in Table I is reasonable. However, it is recommended that the model proposed by the Space Environment Branch (MSC)[5] be used in future studies.

In summary, it is believed reasonable to assign a factor of $10^{\pm 1.1}$ in probability of penetration for a given spacecraft wall due to the uncertainties in the environmental model used in the study.

2.2 Penetration Mechanics

The assumptions used in the study are summarized in Table II (a,b,c) below.

TABLE IIa

Penetration, p, in particle diameters, d, is given by

$$\frac{p}{d} = 2.28 \left(\frac{\rho_p}{\rho_t} \frac{v}{c} \right)^{2/3}$$

The Ames penetration law - ρ_p and ρ_t are the projectile and target densities, v the projectile velocity and c the velocity of sound in the target.

Thickness, T, of plate just punctured

$$T = 1.7\ p$$

Thickness, T, of plate just failing by spallation

$$T = 2.0\ p$$

Following the Ames equation, the thickness of aluminum equivalent to a given single wall is

$$t_{Al} = \left(\frac{\rho_t\ c}{\rho_{Al}\ C_{Al}} \right)^{2/3} \times t_{wall}$$

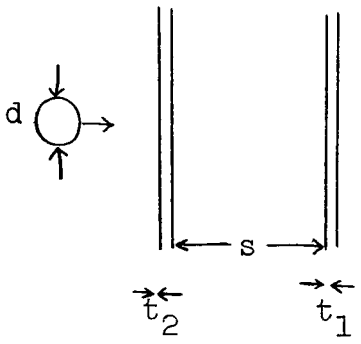
where ρ_{Al} is 2.7 gm/cc and C_{Al} is 5 km/sec.

TABLE IIb

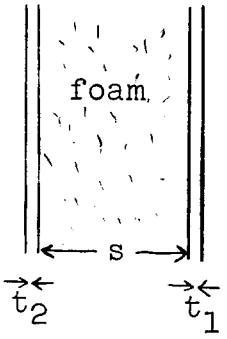
Bumper Factors: two sheet.

For each structure, the equivalent single skin has thickness, t. The thicknesses t_i are equivalent aluminum thicknesses.

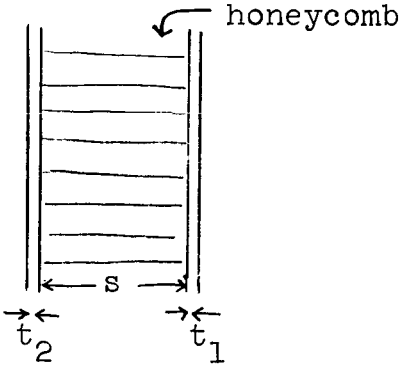
$$t = \frac{t_1 + t_2}{k}$$



s/d	k
8	0.5
12	0.35
16	0.20



s/d	k
8	0.33
12	0.25
16	0.14



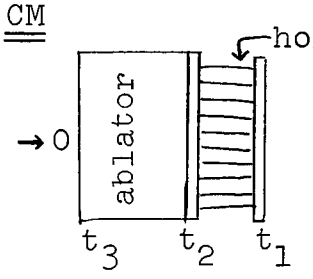
s/d	k
8	0.67
12	0.47
16	0.27

TABLE IIc

Bumper Factors for Composite Walls

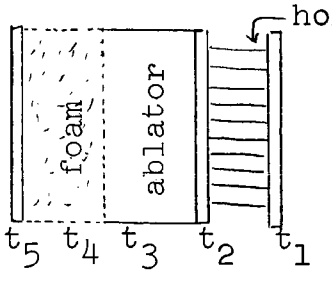
The thicknesses t_i are standard or equivalent thicknesses of aluminum (or stainless steel).

CM



$$t = \frac{t_1 + t_2 + t_3}{0.4}$$

ρ ablator = 35 ※/ft^3



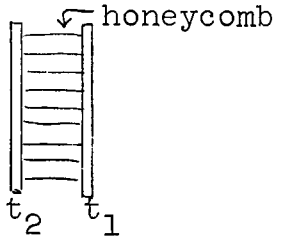
$$t = \frac{t_2 + t_3 + t_4 + t_5}{0.14} + t_1$$

$t_5 \equiv 0.01"$ $\quad t_4 = 1.0"$

ρ foam = 3 ※/ft^3

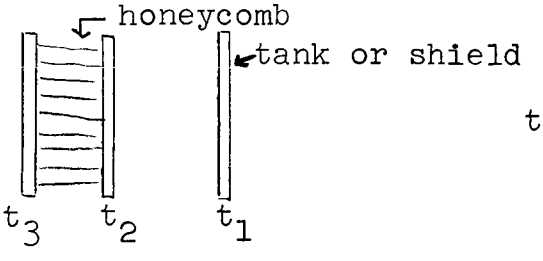
Δ weight in t_2 or t_5

SM

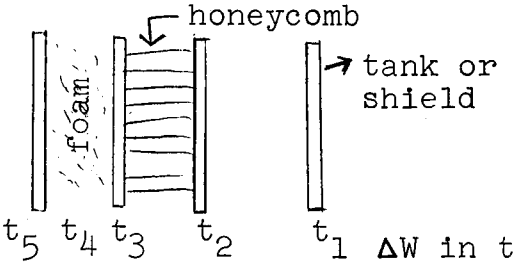


$$t = \frac{t_1 + t_2}{0.67}$$

Δ W in t_1 or t_2



$$t = \frac{t_2 + t_3}{0.67} + t_1$$



$$t = \frac{t_3 + t_4 + t_5}{0.14} + t_1 + t_2$$

$t_5 = 0.01"$ $\quad t_4 = 1"$

ΔW in t_1 or t_5

2.2.1 PENETRATION EQUATION

The ARC penetration equation[6] used in the study is in excellent agreement with experimental data in the hypervelocity range. Its use for impacts occurring at 30 km/sec^{-1} is probably conservative but is to be preferred to use of either the Bjork[7] or Herrman-Jones[8] relationships, which are certainly optimistic. It is even more certain that the ARC equation should be used when the bumper factors listed in the table are considered, since the prime authority for these factors is Summers (ARC), who states that the experimental data obtained on bumper walls are inconsistent with either of the other two relationships.

Another and perhaps greater source of uncertainty is the application of these equations, based primarily on experiments with homogeneous particles of high density to "dustball" meteoroids. The homogeneous model meteoroid, as mentioned earlier, is probably a conservative approximation.

The uncertainty due to these factors may be estimated as a factor of $10^{+0,-1}$ in probability of penetration for a given wall design.

2.2.2 PUNCTURE AND SPALLATION: BUMPER FACTORS

Use of a strict proportionality between wall thickness punctured (or spalled) and crater depth implies that the cratering process dominates the deformation of the wall. This is not a bad assumption for a single wall, although the factors used may not prove conservative at higher impact velocities.

Strict proportionality is very unlikely for meteoroid bumpers, since neither the first (bumper) nor the second (structural) wall defeats impact by a cratering process.

The k factors of Table IIb and IIc are consistent with empirical results and are adequate for the calculation of current reliabilities in the Block II study but are believed to be inadequate for design purposes, since they appear to underestimate the effectiveness of a well designed bumper and

overestimate the usefulness of less optimized multiple walls. A tentative bumper design model is discussed in Appendix A; some of the relevant consequences are summarized below.

(1) The bumper wall should be thin (under .010").

(2) Bumper factors will improve with the square of the spacing. A critical spacing will be necessary to avoid spallation of the structural wall.

(3) Structural walls will be designed to withstand meteoroid impulse spread over a broad area.

(4) For weight equivalent to current structures, nominal k factors of 0.1 and less should be achieved. The potential decrease in puncture probability amounts to at least 2^4 = 16x, and possibly much more.

Qualification of such bumper design will require some confidence that real dustballs are properly vaporized by the bumper.

Minor disagreement on the assignment of k factors in Table IIc results in an uncertainty of $10^{\pm 1.0}$ in probability of penetration for a given wall. In addition the realization of good bumper design could easily affect reliabilities as computed in the Block II study by $10^{+0,-2}$.

2.3 Failure Modes

During the Block II study the following assumptions were made:

NAA C/SM Study:

(a) No impingement of debris on a pressurized fuel tank is permissible.

(b) Complete penetration of the heat shield (and the first stainless steel sheet) is permissible.

(c) All impacts will be normal.

GAEC LEM Study:

(a) No penetration of the spacecraft skin is permissible.

(b) All impacts will be normal.

2.3.1 PRESSURIZED TANKS

Tanks may fail either by puncture or by catastrophic fracture. In checking opinions (including that of the manufacturer of the SM tanks) in regard to this hazard, extreme caution was evinced. It appears, however, that for most test conditions[9,10] puncture is a prerequisite for fracture. Therefore, the assumption of no impingement seems very conservative. Any quantitative discussion is hampered since we do not know the nature of the projectile.

If the tanks are protected only by a bumper skin, and if the bumper generates a divergent cone of vaporized metal, it is clear that for some spacing, perhaps 10 inches, no damage can occur.

If the tanks are protected by a double wall, the most probable projectile is a spall, or scab; spacing is no longer effective, and some kind of nick or more severe damage may ensue.

Under static conditions the SM tanks have a satisfactorily low sensitivity to small cracks, and there are indications that the dynamic situation is not too different. Consequently the assumed failure modes must be regarded as conservative but an alternate assumption must wait on some experimental work.

2.3.2 HEAT SHIELD

Tests at Avco have shown that operation of the ablator is not affected by the removal of one cell of material.. Preliminary hypervelocity impact experiments[11] have indicated that damage will, in general, be limited to a single cell; consequently, complete penetration would appear permissible. Some uncertainty remains as to the possibility of extensive fracturing of the ablative material, suggested by earlier experiments[12], if impact takes place when the ablator is at low temperature.

2.3.3 COMPLEX WALLS

Several of the spacecraft structures considered in the Block II study consist of complex multiple walls. It is important to note that the mode of failure of such complex structures is not quantitatively understood. Only the first wall acts as a meteoroid bumper. Any penetration of the second, or subsequent, walls will launch spalls (see Appendix A), or at least solid fragments, of both unknown size and unknown velocity. Consequently any quantitative treatment is in doubt. The treatment indicated in Table IIc earlier of considering walls other than the first two with a bumper factor of unity is not unreasonable, but further investigation is highly desirable before design actions are taken.

2.3.4 NORMAL IMPACT

The assumption of normal impact is supported by experimental data[13] which indicates little change in penetration of thin skins, or bumpers, with angle of incidence. Further, spall tends to be ejected normal to the surface of the wall under any circumstances.

2.3.5 FAILURE ANALYSIS

In general, the Block II study has proceeded with the assumption that any penetration of the spacecraft is hazardous (exceptions are noted in the case of the heat shield and in parts of the NAA analysis which consider partial penetration of fuel tanks). This is a naive assumption but its use is largely forced by the lack of knowledge of the failure modes of complex walls discussed above.

2.4 Reliability Goals

The overall reliability goals for the Apollo system are 0.999 for crew safety and 0.9 for mission success[14]. However, the spacecraft contractors were explicitly instructed to exclude the effect of meteoroid and radiation environments from the apportionment of reliability to subsystems. It should further be noted that uncertainty of the lunar surface

characteristics has caused the implicit exclusion of the uncertainties inherent in landing from the reliability apportionment. Consequently the effect of the three major space environment hazards on the reliability goals is, as yet, unconsidered. This situation is further compounded by apparently conflicting statements in various Apollo program documents.

Three possible approaches to this problem appear reasonable:

(a) to include the space environmental hazards within the present reliability goals,

(b) to assign separate reliability goals with respect to these environmental factors,

(c) to approach the problem pragmatically.

2.4.1 INCLUSION WITHIN CURRENT GOALS

Logically the primary space environmental factors should be considered in the same way as all other natural, or induced, environments (i.e. as a stress to be met by the appropriate subsystem while still obtaining satisfactory performance). Consequently they could be considered as inducing failure modes in components and subsystems and no specific apportionment of the reliability goals would be necessary. This approach, however, does not recognize the different character of space environmental hazard estimates, the particular solutions, or the fact that they are being included after considerable design has taken place.

An alternate could be to consider the environmental factors as major subsystems of the spacecraft with specific reliability apportionment and subsequent rebalancing of the spacecraft design. In either case the reliability goals for the currently considered subsystems would have to be upgraded. This would appear to be not only difficult but disruptive. It would further appear difficult to ensure the high degree of reliability with respect to the environment which would be required.

2.4.2 SEPARATE GOALS

Somewhat more flexibility and less disruption to the present design with respect to reliability would be achieved by assigning separate reliability goals for the Apollo system with respect to primary space environmental factors. It would not appear inconsistent to assign goals of 0.999 for crew safety and 0.90 for mission success with the subsequent acceptance of the lower overall goals of 0.998 and 0.81 respectively. It should be pointed out that for these environmental factors there is little distinction between crew safety and mission success. Consequently if 0.999 is achieved for crew safety the probability of mission success will be very close to that value. Thus the overall goals are more likely to be 0.998 and 0.89 respectively.

As a result of such an action the initial effect of inclusion of these factors in design would be a reallocation of weights between subsystems but a lesser perturbation on reliability allocations between the hardware subsystems. Subsequently reliability weight trade-offs could be made between the various environmental factors with the advantage that these trade-offs would be considering like uncertainties.

2.4.3 PRAGMATIC APPROACH

A more pragmatic approach may be used to derive appropriate reliability goals based on the weight penalties involved. The argument varies somewhat for the particular factor considered; we will, here, consider the meteoroid environment.

In practice, protection against meteoroids is primarily offered by the walls of the spacecraft which have already been designed with respect to the performance factors such as structural loads. Consequently a weight has already been assigned to these walls. If we consider this weight as utilized in the optimum manner for meteoroid protection we obtain a target reliability. In practice, because of other constraints, the actual protection will be lessened.

We may then consider the additional weight needed to modify (or patch) the structure to raise the reliability to the target level. It would appear logical that the weight penalty for a given increase in reliability would be considerably less below the target level than above as indicated in Figure 1 below. Consequently the pragmatic selection of an acceptable weight penalty and the subsequent acceptance of a reliability close to the target level would not be unreasonable.

The preliminary results of the Block II study further indicate that the reliability so achieved would be close to 0.999 for crew safety, which when coupled with the uncertainties in this estimate already discussed would appear satisfactory. Consequently the differences between this approach and that of separate goals appear primarily philosophical. However, this pragmatic approach reflects more accurately the practical procedures which must, in fact, be followed.

2.5 Recommended Actions

The estimated probability of puncture of the current Apollo spacecraft is developed in Appendix B. The expected values for crew safety are: for the CM, .9997; the SM, .09; the LEM, .07. Consequently, action is certainly required for both the SM and LEM.

The major spacecraft contractors (NAA and GAEC) should be instructed to include protection against the meteoroid environment in their reliability and weight apportionment budgets.

Engineering models of both the environment and penetration mechanics should be supplied by ASPO and the contractors instructed to proceed with failure mode studies and the design of practical bumper configurations.

Specific directions which should be followed for the spacecraft subsystems are outlined below.

2.5.1 COMMAND MODULE

No action appears necessary.

2.5.2 SERVICE MODULE

Three possible options are outlined in Table III below.

TABLE III

Option	Program Disturbance	Weight Penalty	Sensitivity to Uncertainty	Merit
(a) Redesign SM wall	Drastic	Least	Small if bumper spacing is variable	2
(b) Addition of bumper wall (& foam)	Moderate	Small		1
(c) Catcher plate behind present wall	Small	Severe	Large	3

The relative weight penalties for the latter cases are being developed by NAA as part of the Block II study and will not be discussed quantitatively here.

As indicated in the Table, option (b), the addition of an outer 0.01" bumper wall of aluminum separated from the present SM skin by a 1" layer of light* foam, is preferred.

The weight of such a bumper (from meteoroid considerations only) would be 70 lbs for the aluminum wall and 140 lbs for the foam, for a total weight of 210 lbs.

Should the bumper wall be required to be excessively thick because of the launch environment, then option (a) should be considered as an alternate.

* The value 3 lb/ft^3 has been mentioned, and is used here. Foams as light as 1 - 1.5 lb/ft^3 may be equally effective.(15)

2.5.3 LUNAR EXCURSION MODULE

The 0.006" aluminum thermal shield of the LEM should act as an excellent bumper wall. Where necessary, a second skin should be added at least 2" behind the thermal shield, to raise the thickness of the inner skin to at least .012" on the descent stage and .018" on the ascent stage.

The associated weight penalty is estimated to be 62 lbs for the ascent stage and 40 lbs for the descent stage.

2.5.4 PERFORMANCE SUMMARY

A summary of the performance calculated following the actions recommended above is given in Table IV.

TABLE IV

Spacecraft Subsystem	Weight Penalty	Crew Safety Probability	Mission Success Probability
CM	0	0.9997	0.9997
SM	210	0.9997	0.9997
LEM-Ascent Stage	62	.997	.992
LEM-Descent Stage	40	.998	.965
Totals	312 pounds	.995	.957

The assumptions made in performing the analysis to obtain the values listed above are given in Appendix B.

2.5.5 EFFECT OF THE UNCERTAINTIES: RELIABILITY

In estimating the reliability of a given structure, the uncertainties in impact probability enumerated above must be compounded. The common logarithms of these uncertainties are listed in Table V.

TABLE V

Common Logarithm of Uncertainties in Damage Probability For a Given Wall

Source	Error in Quantity	Error in Probability (or flux)
1) Meteoroid mass	±0.5	±0.67
2) Extrapolation	±0.5	±0.67
3) Ames Eqn.(structure)	~(+0,-.25)	-0.5 ±0.5
4) Bumper factors (unc)	±.25	±1.0
5) For best wall	(0,-0.5)	-1.0 ±1.0
* * * *		
(Errors are combined independently)		
Probable deviation	Σ(1-5), best wall	-1.5 ±1.8
Uncertainty in current estimate	Σ(1-4)	-0.5 ±1.5
Uncertainty in environment	Σ(1-3)	±1.1

An impact rate, then, assuming independent, random errors, can be expected to be incorrect by 60 times. An expected improvement due to the use of improved bumper technology of 30 times is conservative.

2.5.6 EFFECT OF THE UNCERTAINTIES: WEIGHT

If a bumper wall is used for protection, it seems likely that the weight penalties associated with the uncertainties can be allotted solely to increasing bumper spacing. The importance of this can be seen from the tentative bumper model (Appendix A) in which "bumper factor" varies as the square of bumper spacing.

Unless dense foam spacers are used, it will always be economical in weight to adjust spacing.

It is then clear that the recommendation to employ bumpers with variable spacing is firm, and that the weight penalty is not strongly affected by the flux uncertainties.

3.0 FUTURE PROGRAM

In this section an attempt will be made to list and discuss briefly on-going programs and recommended actions which will reduce the current uncertainties in the meteoroid hazard.

3.1 Meteoroid Environment

3.1.1 RADAR METEOROID STUDIES

As mentioned earlier, the meteoroids of primary interest to the Apollo system comprise the faint radar range. Consequently one of the more important sources of information is the on-going Harvard Radio Meteor Project funded by ART, SSA, and MSF.

Their efforts should aid in:

(a) relating the radar and visual meteor data with a resultant improvement in certainty of the flux-mass relationship;

(b) increasing understanding of the structure of cometary meteoroids, their mass, density, and velocity distribution; and

(c) obtaining improved data on temporal and spatial flux variations with particular regard to meteoroid showers.

3.1.2 FLIGHT EXPERIMENTS

The direct penetration measurements obtained from meteoroid satellite flights are important not only in their own right but because they provide an independent check of the validity of the combination of the visual and radar meteor data with ground-based hypervelocity experimental relationships.

SA-9 and 8:- These flights will give measure of the meteoroid fluxes capable of penetrating single skins of aluminum of .0015", .008", and .016" thickness. The latter will provide a direct estimate of the number of punctures for the current outer wall of the SM.

SA-10:- This flight is currently fixed as a minimum perturbation of the SA-9 and 8 spacecraft. Its value would be greatly increased if:

(a) some form of bumper structure could be flown to provide a flight test of bumper effectiveness;

(b) thicker sheets of aluminum up to, perhaps, 25 mils of aluminum could be used.

S-55:- The satellites, similar to Explorer XVI, have small exposure but will give valuable information concerning:

(a) impact on various materials,

(b) the action of scaled-down bumper walls,

(c) the structure of smaller meteoroids.

Close liaison is being maintained with all these programs.

3.2 Penetration Mechanics

In this section we will restrict the discussion to meteoroid bumpers and general failure mode studies.

3.2.1 METEOROID BUMPERS

A proposal has been submitted to the Structures Division, MSC, by General Motors Corporation for a combined experimental and theoretical study of meteoroid bumpers and second wall behavior. The proposal is well considered and proposed by a group of extreme competence in the field of hypervelocity impact phenomena. It is to be stressed that the theoretical support of the experiments is of paramount importance. This study should be strongly supported and initiated as soon as possible.

Somewhat separate is the problem of obtaining more experimental information on some of the more complex structures involved in the Apollo spacecraft ranging from the five-layer heat shield/CM wall to spacesuit fabric. Current data is far too fragmentary, scattered and incomplete. A more complete, integrated empirical study appears necessary which could perhaps be carried out in conjunction with ARC.

3.2.2 PRESSURIZED FUEL TANKS

LeRC and Boeing have current studies on this problem. Closer liaison should be maintained with these studies and an attempt made to integrate them, to some extent, with the proposed GM or ARC studies discussed above. Full scale or simulated, proof tests of the SM tanks should be required as part of the development program.

3.2.3 HEAT SHIELD PENETRATION

Further experiments should be conducted with ARC on the effects of low temperature impact on the ablative material.

3.2.4 FAILURE MODE STUDIES

As part of subsequent development activities the major spacecraft sub-contractors should be required to perform a careful, documented review of the sensitivity of the various spacecraft components to both primary impact and spall. Subsequently a more sophisticated analysis of the complete spacecraft should be performed with a solid angle breakdown analogous to similar studies already completed for the radiation environment.

4.0 CONCLUSIONS

A summary and recommendations are contained in the letter included at the beginning of this report. It should, however, be noted here that this report is concerned with the current status of a large and complex problem. Consequently it has contained a number of statements supported only by engineering judgment, although every effort has been made to obtain stronger supporting evidence wherever possible.

It is further noted that this report is not complete in itself but should be considered together with the results of other parts of the Block II meteoroid study and with earlier analyses of the meteoroid environment.

B. T. Howard

G. T. Orrok

1111-$\frac{\text{BTH}}{\text{GTO}}$-tj

APPENDIX A

Protection Technology

In this appendix, protection technology is reviewed. A tentative bumper model is presented; while this has some order-of-magnitude validity, its prime purpose is to exemplify the physical processes in bumper operation.

Penetration in Semi-infinite Targets

The Block II decision meteoroid model utilizes the Summers (or Ames) penetration law to predict damage to various targets. As originally formulated, the crater depth following normal impact on a semi-infinite target, p, is related to the (spherical) projectile diameter, d, by the equation

$$\frac{p}{d} = 2.28 \left(\frac{\rho_p}{\rho_t} \frac{v}{c} \right)^{2/3} \qquad \text{(A-1)}$$

where ρ_p and ρ_t are the projectile and target densities, v is the projectile velocity, and c is the velocity of sound in the target. For impacts on plates, the following rules are used. T, the thickness of plate just penetrated by the projectile, = 1.7 p; the thickness of a target just failing by spall is 2 p. Thirdly, utilizing a meteoroid bumper configuration, $t_1 + t_2$, the total wall thickness, = kT, where k, a "bumper factor" less than one, is listed for various configurations.

Of course, no hypervelocity experiments have been performed at impact velocities approaching 30 km/second. The variation of penetration depth p with projectile density, structure (impact by fairy castle!), and angle of incidence is very poorly defined.

Best current opinion (J. Summers) is, however, that equation (A-1) fortuitously predicts about the correct penetration for the current model meteoroid; this is, p/d = 2.4x for a projectile of density 0.5 gm/cc and velocity 30 km/sec impacting normally on a semi-infinite aluminum target. If anything, this relation is

conservative, possibly by 20% in crater depth. Some effects of material strength or a momentum dependent penetration law could contribute.

Any conservatism is counterbalanced in that the thin plate perforation and spallation factors are probably too small.

Meteoroid Bumpers

Beyond this, current design procedure for meteoroid bumpers is misleading. In all probability it leads to great misuse of weight allotted to meteoroid protection.

In Table IIb of the text, a current "bumper factor" table is shown. As stated above, where t_i is one element of a multiple wall,

$$\sum_i t_i = kT \qquad \text{(A-2)}$$

where T is the thickness of equivalent single wall which will stop the projectile, as predicted by the Ames law.

This kind of presentation only represents the proof tests from which it was constructed. It does not adequately describe a good meteor bumper structure, nor does it give insight into the behavior of more complex structures.

The meteoroid bumper was first suggested by Professor Whipple in a Project Rand study in 1946. The following quotation is from the earliest convenient reference[16]. The bumper, "consists simply of a secondary thinner skin ... located outside of the primary skin at a distance of a centimeter or two. Because of the high velocities involved, such a meteoroid would explode violently upon encountering a layer comparable to its own dimension. Since the kinetic energy is far above the molecular binding energies in the solid, a simple consideration of the momentum and energy equation will show that an explosion must occur.

"The debris from the explosion will spread over a large solid angle and consequently encounter the inner skin of the vessel over a much larger surface area than that of the original meteoroid.

The degree of penetration will be reduced by a large factor even though the energy of the meteoroid has not been greatly reduced."

We now develop an order of magnitude model describing this.

Bumper Wall

The first, or bumper wall, is designed to arrest the meteoroid briefly and "explode" it. Since this requires high impact velocities, it is perhaps not surprising that it is only recently that liquefaction and vaporization of projectile and bumper wall have been observed. C. J. Maiden[17] emphasizes the importance of this, and presents a conservative, empirical condition on the thickness of the bumper wall, t_b, relative to meteoroid diameter:

$$t_b/d > 1/8. \qquad \text{(A-3)}$$

This is for impacts of like materials. It is empirically valid for (low melting point) cadmium projectiles on cadmium targets above 6 km/second, and (theoretically) for aluminum above the 7-10 km/sec range. Maiden finds that for bumper walls of materials other than projectile material, an equal mass per unit area is required. Thus,

$$\frac{t_b}{d} > \frac{1}{8}\frac{\rho_p}{\rho_t} \qquad \text{(A-4)}$$

is a plausible form for the design of a bumper wall. A numerical example will be given below*.

It should be noted that a bumper wall thicker than the critical thickness offers no advantage for meteoroid protection until it becomes appreciable to the "equivalent single skin". It is then no longer a "bumper wall" in the strict sense.

---

* Dustballs can be hypothesized with "pathological" structures which will not be vaporized by such a wall. The foam filled bumper (not considered here) should be markedly more efficient with these.

Spacing

Now, the spacing of the bumper from the structural wall should be chosen, with due concern for the failure modes of that wall. The "exploded" meteoroid distributes the projectile momentum within a cone of about 45° half angle. The distribution of momentum within this cone has not been determined.

The structural wall may fail (a) by surface attack or cratering, (b) by spallation from its rear surface, or (c) by mechanical response to the total impulse (tearing or excessive deflection).

(a) Surface Attack

If the bumper wall is sufficient, surface attack is empirically negligible[17]. A back-up plate spaced an inch or so is coated with a "splash" of projectile and bumper material, and pitted a minimal amount.

Conditions for (b) and (c) have not been worked out. The following order of magnitude arguments indicate the way in which design might proceed.

(b) Spallation

Spallation occurs as follows. A high intensity compressive shock is imparted to a plate. This is reflected from the after surface as a tension wave (Figure A1). The pressure at the free surface is always zero, so that maximum tensile stress occurs along a plane somewhat within the material. If the stress exceeds the fracture stress of the material, a spall may separate from the reverse of the plate.

The precise mode of failure has been studied experimentally by O'Brien[18]. For five face-centered cubic metals, dynamic fracture stresses proved to be about 1/10 of the calculated theoretical strength. O'Brien concluded that fracture was nucleated at individual imperfections (dislocations) in the metal. The stress was relatively

independent of alloying constituents, hardness, and temperature, its magnitude correlated well with 1/10 of the bulk modulus, B.

The magnitude of the impact stress may be estimated as follows:

The momentum incident on the structural wall is about the projectile momentum. Since this is dispersed in a 45° cone, the area of application is πs^2, where s is the bumper spacing (Figure A2).

The instantaneous pressure, P, can be crudely estimated by dividing the impulse/area by a time of application, Δt. Then,

$$P \sim \frac{m \quad v}{\pi \; s^2 \; \Delta t} \tag{A-5}$$

A reasonable time is that required for the meteoroid to travel its own length, $\Delta t = d/v$. Substituting this, and expressing the meteoroid mass as $\rho_p \; \pi \; d^3/6$, we obtain

$$P \sim \frac{\rho_p \; v^2 \; d^2}{6 \; s^2} \tag{A-6}$$

If the structural wall is thin, the stress wave will be nearly plane, and will not be substantially attenuated by traversing the plate. Reflected in tension, spallation will occur unless

$$\frac{B}{10} \sim \text{fracture strength} > P \tag{A-7}$$

The bulk modulus, B, and Young's modulus are not very different, and it is reasonable to express B in terms of the velocity of elastic waves, i.e. $\rho_t \; c^2 = B$. The condition for avoiding spall damage becomes

$$\rho_t \; c^2 > \frac{10}{6} \quad \frac{\rho_p \; v^2 \; d^2}{s^2} \quad , \quad \text{or}$$

$$\frac{s}{d} > 1.3 \sqrt{\frac{\rho_p}{\rho_t}} \; \frac{v}{c} \tag{A-8}$$

To avoid spall, then, a condition on spacing alone (not on the thickness of the structural wall) is obtained. The precise functional form would be expected to differ somewhat from the above.

(c) Deformation of the Structural Wall

If spallation has been avoided, the shock decays. The structural wall is now moving, in response to the impulse communicated to it. The resultant stresses should be amenable to conventional structural analysis, or for that matter, to direct test, the impulse being applied in the laboratory in any convenient way*. Johnston, Knapton, and Lull[19] have analyzed a case of elastic flexure of an infinite plate wall, assuming a Gaussian radial distribution of momentum incident from the meteoroid "explosion".

The impulse gives the initial velocity distribution on the plate. They compute the stresses which occur as a function of time, obtaining for the maximum (their equation (7), p. 69)

$$\sigma_{max} = \sqrt{\frac{3}{4\,(1-\mu^2)}\,\frac{E}{\rho_t}}\;\frac{I}{t_\omega\,\pi\,s^2}\;0.65 \qquad \text{(A-9)}$$

Here, E is Young's modulus, $\mu \sim 0.3$ is Poisson's ratio, I the total impulse $\sim mv$**, and t_ω the thickness of the structural wall. They suggest a criterion that the maximum stress be held under the elastic limit $\sigma_{E.L.}$ of the material; that is, the wall shall not take a permanent set.

$$\sigma_{max} < \sigma_{E.L.} \sim \frac{E}{500} \qquad \text{(A-10)}$$

---

* The heating due to impact might need to be compensated for in a low velocity experiment.

** If there is substantial back splash from the wall, this would be doubled. We have also ignored any momentum multiplication in the bumper interaction.

Often the elastic limit is described as that stress which causes 0.2% elongation of the specimen, which gives the E/500 equivalence.

This condition can be put in a form more consistent with those above by substituting $E \sim \rho_t c^2$, and $I = \rho_p v d^3 \pi/6$.

$$\left(\frac{s}{d}\right)^2 \frac{t_\omega}{d} > 50 \frac{\rho_p}{\rho_t} \frac{v}{c} \qquad \text{(A-11)}$$

Thus, for this restrictive combination of assumptions, the second wall thickness, t_ω, required, is proportional to particle velocity and inversely proportional to the square of the bumper spacing. The functional dependences seem reasonable*. The coefficient would certainly be markedly different for an engineering structure such as a honeycomb wall.

Numerical Example

Suppose a space mission with an exposure of 10^8 m^2 sec. If we wish to protect to a reliability of .999, we must defeat according to the meteoroid model a meteoroid of mass about $10^{-5}/3$ kg. At a density of 500 kg/m^3, this is a diameter of 2.3×10^{-3} m. In English units of thickness, this is 90 mils.

We summarize the equations above for impacts of the model meteoroid on aluminum

$$\text{Bumper wall:} \quad \frac{t_b}{d} > \frac{1}{8} \frac{\rho_p}{\rho_t} = \frac{0.5}{82.7} = \frac{1}{43} \qquad \text{(A-12)}$$

$$\text{Spacing:} \quad \frac{s}{d} > 1.3 \sqrt{\frac{\rho_p}{\rho_t}} \frac{v}{c} = 3.4x \qquad \text{(A-13)}$$

$$\text{Back wall:} \quad \frac{t_\omega}{d} \left(\frac{s}{d}\right)^2 > 50 \frac{\rho_p}{\rho_t} \frac{v}{c} = 56x \qquad \text{(A-14)}$$

* Note the lack of resemblance to any ordinary penetration law.

For this example, a two mil bumper wall would suffice. A minimum of 0.3 inch spacing is necessary to avoid spallation; a 2" spacing would, however, give a reasonable back wall thickness of $t_\omega/d > 1/10$, or about a 10 mil structural wall*.

Clearly this is a very optimistic order of magnitude model. We can compute the "k" factors obtained as follows. From the Summers criterion, with T = 2p, we obtain the thickness of single wall:

$$\frac{T}{d} \sim 4.6 \left(\frac{\rho_p}{\rho_t} \frac{v}{c}\right)^{2/3} \tag{A-15}$$

The equivalent total bumper structure thickness is

$$\frac{t_b + t_\omega}{d} = \frac{\rho_p}{\rho_t} \left\{\frac{1}{8} + 50 \frac{v}{c} \left(\frac{d}{s}\right)^2\right\} \quad ** \tag{A-16}$$

The "bumper factor" is

$$k = 11 \left(\frac{\rho_p}{\rho_t} \frac{v}{c}\right)^{1/3} \left(\frac{d}{s}\right)^2 \left\{1 + \frac{c/v}{400} \left(\frac{s}{d}\right)^2\right\} \tag{A-17}$$

For the model meteoroid,

$$k = 11 \left(\frac{d}{s}\right)^2 \left\{1 + \frac{(s/d)^2}{2400}\right\} \tag{A-18}$$

Equation A-8 must be satisfied to withstand spall, so $s/d > 3.4$; with this condition, $k < 1$. Note that for $s/d \sim 50$ (a 5" spacing for our example) the two walls are equal in thickness and $k \sim .01$. This seems very optimistic, but perhaps not implausible.

These are, of course, order of magnitude calculations. Their principal use should be in guiding studies of bumper design.

---

* With regard to the structural wall, the particle momentum is $10^{-5}/3$ kg times 3×10^6 m/sec or 10^{-1} kg m/sec. This is comparable to a weak blow from a carpenter's hammer.

**For $s/d \ll 50$, the second term predominates. Note that the velocity and density dependences differ from those of the Ames criterion. This is to be expected. The "failure modes" are different.

Criticism of the "k factor" Concept

The "k factor" concept as used in the Block II decision study conflicts clearly with the results of this study.

Firstly, for $(s/d) \ll 50$, almost all the material thickness should be on the structural wall if high k factors are to be obtained. The k factors of Tables IIb and IIc allow any weight distribution between bumper and structural walls.

Secondly, both equation A-18 and the empirical k factors of Table IIb show a strong dependence of k factor on (s/d). This has not been emphasized sufficiently in the Block II study. To see the importance of this, suppose that due to the uncertainties a rather larger meteoroid than expected must be defeated. Use of Table IIc would suggest that the walls be thickened. If the old and new meteoroid diameters are d_o and d_n, then the total wall thicknesses t_o and t_n, vary in direct proportion. Thus,

$$\frac{d_n}{d_o} = \frac{t_n}{t_o} \tag{A-19}$$

In fact, we must write

$$\frac{d_n}{d_o} = \frac{t_n}{k_n} \cdot \frac{k_o}{t_o} \tag{A-20}$$

where k_n and k_o are the bumper factors, expressed as functions of (s/d). For the tentative model, assume that the bumper wall is adequately thick, that $s/d \ll 50$ (the thickness t_n and t_o now refer only to the structural wall), and use equation A-18). We then obtain, from (A-20),

$$\left(\frac{d_n}{d_o}\right)^3 = \frac{t_n}{s_n^2} \frac{s_o^2}{t_o} \tag{A-21}$$

Comparison of equation (A-19) and (A-21) shows that, because the k factor is a function of particle diameter, the addition of weight to spacecraft walls is an inefficient means of adjusting to the uncertainty in the meteoroid hazard.

Conclusions and Recommendations

As exemplified in these order of magnitude calculations, a real understanding of the operation of meteoroid bumpers -- at least as far as solid projectiles are concerned -- may not be too far away.

Experimental and theoretical work should be strongly directed at

(1) The nature of the ejecta from the bumper wall -- its physical state and angular distribution. This may be strongly sensitive to the angle of incidence of the projectile.

(2) Failure modes of the second, structural wall. Spallation failure may not require too much further work. Studies of the gross deformation of the second wall should have a close tie between empirical and analytical methods.

(3) Unmentioned above is the behavior of foam fillers. It appears that low density foams (1/10 gm/cc and less) are effective in reducing damage or, in two-inch thickness, defeating lower velocity projectiles (7 km/sec). The mode of protection should be analyzed. Particularly if very low k factors prove out, it is doubtful that foams will show any weight advantage over vacuum-spaced bumpers.

(4) Studies of the failure of tanks under ejecta loading, such as those pursued at Lewis, should continue. It would appear reasonable that a peak pressure criterion similar (but more conservative) than that used for spallation could be employed here. Note, however, that if a double wall fails by spall, an entirely different kind of projectile is launched at the tank!

(5) The direct application of these results to meteoroid impact will be limited until dust ball properties are better known. The importance of bumper "proof" in space cannot be overemphasized.

APPENDIX B

The Spacecraft

Neither the incidence of meteoroids nor the optimum protection technology is well defined. The current status of the spacecraft will be described here. Reliability goals have not been set. For the purposes of this appendix, 0.999 is considered excellent and 0.99 satisfactory.

The conclusions of this review are, essentially, that, provided a meteoroid protection problem exists which is beyond the reach of minor patching, it is necessary to use a Whipple meteor bumper, with a thin outer wall and a substantial spacing. It is possible that the weight trade-off might arise principally in ancillary structures necessary to protect the bumper during launch, etc.

We now consider the individual modules, and make some brief comments on each. It will be convenient to have the meteoroid model flux expressed in particle diameters (d, meters) assuming spherical projectiles of density $\rho_p = 0.500$ kg/m^3. N is the flux in $m^{-2}sec^{-1}$. From Whipple's equation (Table I of the text) we obtain:

$$\log N = -21.37 - 4.02 \log d + 4.02 \log \frac{440}{\rho_p} \qquad \text{(B-1)}$$

with the assigned density, this becomes

$$\log N = -21.60 - 4.02 \log d \qquad \text{(B-2)}$$

This relation is shown in Figure B1.

The following numerical values will be useful.

AMES EQUATION

crater depth, p = 2.4x particle diameter

wall not punctured T = 1.7 x p
= 4.1 x particle diameter

wall not spalled T = 2 x p
= 4.8 x particle diameter

The Service Module

Considering the cylindrical body of the SM as a target, and allowing a bumper factor of 0.67 for the honeycomb wall, we find that the expected number of penetrations in a two-week mission is 2.4. The reliability is .09%. The numbers used in calculation are listed in Table B1.

The uncertainties in the estimate may be roughly estimated (as stated earlier) and are listed in Table V of the text. The total mass and extrapolation uncertainties contribute more than an order of magnitude. The structure uncertainty in the model meteoroid is represented as a factor of 10 total uncertainty in density -- an allowed range from 0.15 gm/cc to 1.5 gm/cc. This appears as 2.7 orders of magnitude in the puncture rate!

From Table V, the logarithmic uncertainty in a current estimate (using a bumper factor table) is ±1.5 or 30x. "Expected" puncture rates, then, could range from 75 to .08 per two-week mission.

Table B1

Service Module

Area (walls only) $48 m^2$

Time 14 days 1.2×10^6 sec

Exposure 6×10^7 m^2 sec

Wall 2 x .016" aluminum honeycomb (1/4" cell)
Bumper factor (Table II C) 0.67
Equivalent thickness 1.2×10^{-3} m

CRITICAL PARTICLE d = 1/4.1 thickness = 0.29 mm

FLUX 4×10^{-8} m^{-2} sec^{-1} (from Figure B1)

Table B2

Command Module

Area 20 m^2

Time 14 days 1.2×10^6 sec

Exposure 2.4×10^7 m^2 sec

WALL 0.6" ablator (minimum) plus 2 sheets of stainless steel .008"

Ablator properties: ρ = 0.56 gm/cc. Assumed sound velocity, 2 km/sec.

Thickness of equivalent aluminum = 0.19 ablator

Steel properties: thickness of equivalent aluminum = 2.0
thickness of stainless steel

Bumper factor (Table II C) k = 0.4

Equivalent thickness 9.2×10^{-3} m

Critical Particle 2.25×10^{-3} m diameter

Critical Flux 1.1×10^{-11}

Actions—

Plausible alternative actions might include the following.

(1) Do nothing, since the uncertainty is so great. However, since the minimum estimated puncture rate is still unduly hazardous, it is possible to say with high confidence that redesign of the SM is necessary.

(2) Do nothing, since failure modes are not that serious. Allowing the SM tanks to be just "not penetrated" according to the rules of Table II C reduces the failure probability by about 70x. The nominal reliability would be 0.96; according to the ground rules of this section (0.99 satisfactory), remedial action is desirable even with this liberal (100% penetration) change in failure modes.

It should be emphasized that the honeycomb skin of the SM will probably fail by spallation or by tearing, and that

the nature of the projectile thereby launched at the tank is unknown. Further study is certainly required (a) of failure of the honeycomb, and (b) of the resultant failure of pressurized tanks.

(3) Thicken the honeycomb. Unless the weight penalty is small, it is unwise to use a honeycomb ($k \sim 0.67$) for meteoroid protection. To reduce the puncture rate by 10^3 (i.e. attain .997 reliability), wall thicknesses must increase by $10^{3/4}$. The equivalent single aluminum wall increases from 1.2×10^{-3}m to 6.74×10^{-3}m, a penalty of 1600 pounds. Applied as a bumper structure, the penalty is much less.

k	1	0.67	0.2
Wt	1600 lb	1080	320 lb

(4) Build a bumper skin. It is not improbable that the current skin with the addition of a widely spaced bumper, perhaps foam filled, would have high reliability. If current indications are correct, a very thin bumper -- well under 10 mils -- would suffice. The weight of a 48 m^2 area sheet of this thickness would be 70 pounds. The weight of a 2" foam spacer would be substantial (5500 x sp. gravity lb) unless specific gravities of .01 or so were used. At 3 pounds/ft^3 and 1" spacing, the weight is 140 lb, for a total penalty of about 210 pounds.

It would seem most sensible to put such a bumper on the SM. The nominal estimated reliability under Block II decision rules would be on the order of .9997, but the uncertainty in this value is still so large as to make trade-offs with better defined systems of little quantitative value.

Command Module

Taking the conical surface of the CM, and stating that the first stainless steel sheet but not the second may be punctured, we find an expected number of punctures of 3×10^{-4}. The numerical assumptions are listed in Table B2. The range of rates allowed by the uncertainty is from .01 per mission to about 10^{-5}.

Clearly there is no necessity for drastic action about the CM. Since as stated above the initial weight of the foam in a foam bumper can be substantial, minor adjustments in reliability may best be made by thickening the ablator. If bumpers are considered, for any reason, the jettisoning problem will appear. Particular attention should be paid to sheets (protected during boost) designed to melt and tear off immediately on entering the atmosphere. The possibility of erectable bumpers (balloons) should not be neglected.

Lunar Excursion Module

The LEM offers much more difficulty to even superficial analysis. It comprises a variety of wall thicknesses. Many areas are re-entrant, and see considerably less than 2π steradians. In computing exposures, the time before manning must be allotted to mission success (a small distinction for the CM/SM). On the lunar surface, the LEM is subject to a secondary ejecta flux, which by virtue of its low velocity has unity bumper factor.

The ejecta are in all probability not a matter for concern. As described by Gault, Shoemaker, and Moore[20], fragments ejected from distant craters will contribute a flux which, by mass, is several orders of magnitude higher than the primary flux. As applied by MSC, the factor is $10^{3.83}x$, or 6800.

W. S. Boyle and G. T. Orrok[21] pointed out that in using the Ames penetration criterion, one is concerned with the flux of projectiles having given kinetic energy. Except under unreasonable assumptions, the actual puncture rate of single wall structures cannot be doubled. Gault says currently (private communication) that on an energy basis, the secondaries should be down one or two orders of magnitude. Using the Ames law, the puncture rate of simple structures would be "down" an equal amount.

In addition, secondary velocities are very low. The MSC model secondary meteoroid velocity is 200 m/sec. This is conservative; Figure 10 of reference (20) suggests that it is unlikely that more than 5% of the ejected mass will exceed this

speed. At such low velocities, the Ames equation considerably overestimates penetration. It is described better by the equations of Bohn and Fuchs[22] or Hermann and Jones[8].

Applying the Bohn and Fuchs equation to the model secondary meteoroid, of density 3.5 gm/cc impacting hard aluminum, one obtains a penetration smaller by 4x than that predicted by the Ames law. Since flux (equation B-1) goes as the 4th power of linear dimension, this is an additional factor of 250x reduction in puncture rate.

A current "best estimate" then sets the ejecta puncture rate in single skin as 3 to 4 orders of magnitude below the primary rate. Equivalently, a bumper can afford to "look" 5 or 10x thinner to the ejecta than it does to the primaries before an appreciable increase in puncture rate occurs. In the following discussion no bumper factor lower than 0.2 is used, and the secondaries are ignored.

The LEM external walls comprise a uniform 6 mil thick thermal control surface of aluminum, which should serve admirably as a bumper. Within this are heavier walls where required structurally in the descent stage and in the pressurized regions of the ascent stage. More than half of the surface, however, is the .006" material alone. Grumman propose to reinforce this with a similar secondary wall.

In the 6 mil single wall alone, the expected number of penetrations in five days (essentially the one day landing mission) is thirteen.

The assumptions are listed in Table B3. Note that the current model must be replaced by the Explorer XVI data. On Figure B-2, the model flux versus penetration curve is joined with the direct data.

The uncertainty in this value (12 punctures) is about 2x.

Perhaps 2.5 punctures are chargeable to mission safety.

Table B3

Mission Success for Current LEM

Region with 6 mil single skin alone:

Area	30 m^2	
Time	5 days	4 x 10^5 sec
Exposure	1.2 x 10^7 m^2 sec	
Wall	.006" single skin,	= 1.52 x 10^4 m
Flux	(Fig. B2)	1.1 x 10^{-6}

Alternative Actions

Clearly, until experiment has shown it unnecessary to protect tankage, a bumper wall must be introduced.

Table B4 shows approximate safety and success figures and weights for several configurations. The first three, arbitrarily chosen, correspond to minimum configurations of 6 + 6, 6 + 12, and 6 + 18 mil aluminum sheet, with bumper factors of 0.2.

Because the crew safety exposure of the descent stage is about 5 times less than that of the ascent stage, it has relatively high crew safety values. The next entry assumes a 6 + 18 mil minimum thickness on the ascent stage and a 6 + 12 mil on the descent stage. This corresponds to equalizing the number of crew safety punctures per skin weight. At a hundred pounds, and safety of .995, this is considered a reasonable design target.

Finally, the equivalent computations have been made using the bumper model of Appendix A and the 6 + 6 mil configuration. As expected, the meteoroid problem is negligible.

Table B4 LEM

Configuration	WEIGHT (pounds)			MISSION SAFETY			MISSION SUCCESS		
	Overall	Ascent	Descent	Overall	Ascent	Descent	Overall	Ascent	Descent
As is	0	0	0	.068	.090	.71	$<10^{-5}$	.0005	.004
6+6 min	37	21	16	.959	.966	.993	.77	.89	.87
6+12 min	81	41	40	.987	.992	.998	.94	.975	.965
6+18 min	136	62	74	.996	.997	.9993	.981	.992	.989
6+18 Asc. / 6+12 Desc.	102	62	40	.995	.997	.998	.957	.992	.965
6+6 (Appendix A bumper model)	37	21	16	.99983	.99986	.99997	.9991	.9996	.9995

REFERENCES

1. F. L. Whipple; J. Geophys. Research; 68, p. 4929, 1963.
2. W. A. Lee; private communication.
3. I. C. Browne, K. Bullough, S. Evans and T. R. Kaiser; Proc. Phys. Soc., B-LXIX, 83, 1956.
4. G. S. Hawkins and R. B. Southworth;Research Report No. 2; NASA Contract NASr-158; July 1963.
5. MSC Engineering Criterion Bulletin, EC-1, November 8, 1963.
6. J. L. Summers; NASA TND-94; October, 1959.
7. R. L. Bjork; Rand Corp. Report; P1662; 1958.
8. W. Hermann and A. H. Jones; Proceedings of Fifth Hypervelocity Impact Symposium; 1962.
9. F. S. Stepka and R. W. Morse; NASA TND-1537.
10. G. T. Burch, D. H. Lee and J. F. Lundeberg; ASD-TDR 64-3 (CONFIDENTIAL); January 1964.
11. L. St. Leger; private communication.
12. J. L. Summers; NASA TM X-54, 025; January 1964.
13. J. L. Summers; private communication.
14. Apollo Reliability Program (NAS 9-150) SID 62-203; NAA; May 15, 1963.
15. B. W. Reynolds and R. H. Emmons; Proceedings of the Sixth Symposium on Hypervelocity Impact, 1963, Vol. III, pp. 249-279.
16. F. L. Whipple;"Meteoritic Phenomena and Meteorites", Ch. X, The Physics and Medicine of the Upper Atmosphere, ed. Benson & White, U. of New Mexico Press, Albuquerque, 1962; pp. 155-156.
17. C. J. Maiden and A. R. McMillan; Preprint 64-95, AIAA Aerospace Sciences Meeting, New York, N.Y., January 20-22, 1964.
18. J. L. O'Brien; Fracture of Metals Under Impulsive Loading Conditions, Quartermaster Research & Engineering Command, U. S. Army, Contract D A 19-129-QM-1166, O.I. No. 6140, Project 7-99-01-001; Office of Naval Research, Contract Nonr-1866(35).
19. R. H. Johnston, D. A. Knapton and D. Lull; Meteoroid Bumper Protection for Space Vehicles: Tentative Design Criteria, A.D.Little, Inc., Report No. 65008-05-01, June 1963; NASA contract NASw-615.
20. D. E. Gault, E. M. Shoemaker and H. J. Moore; NASA TN-D 1767; April 1963.
21. W. S. Boyle and G. T. Orrok; Penetration of Spacecraft by Lunar Secondary Meteoroids; Bellcomm Technical Report; June 28, 1963.
22. J. L. Bohn and O. P. Fuchs; ASTIA AD243 106.

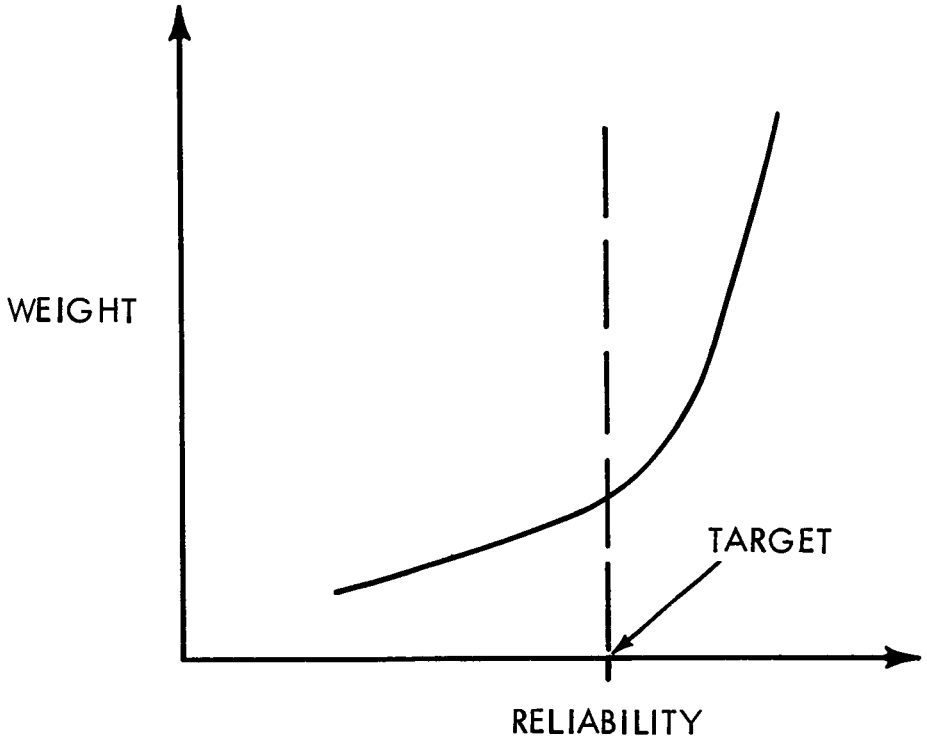
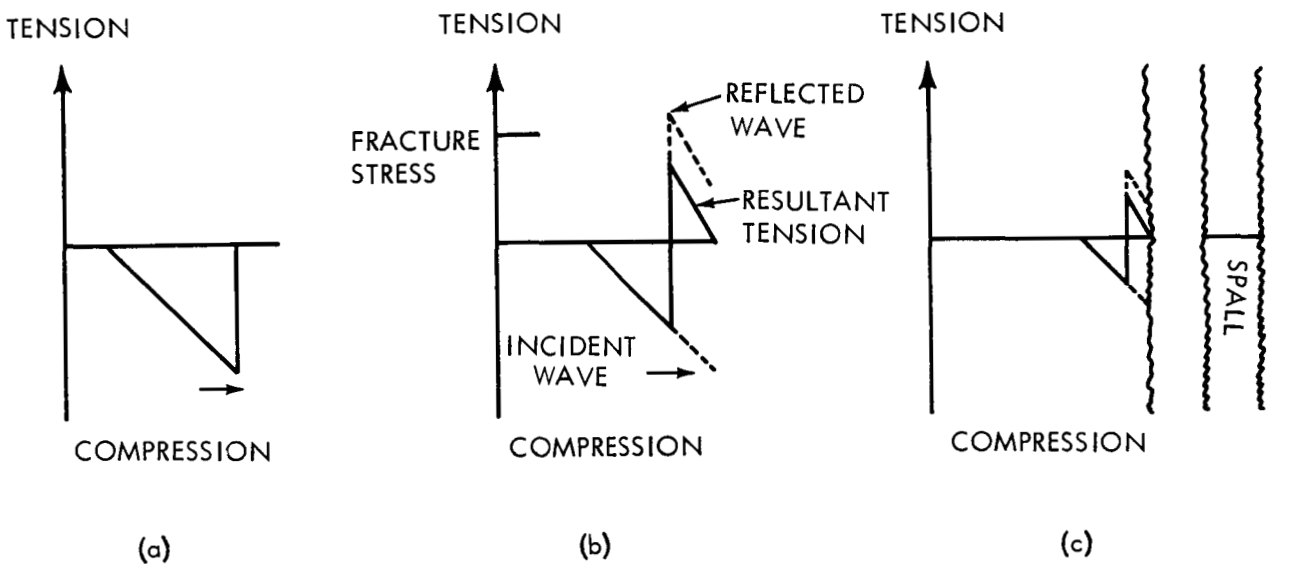


FIGURE 1



REFLECTION OF COMPRESSION WAVE IN TENSION INDICATED

(a) COMPRESSION WAVE TRAVELING TO THE RIGHT APPROACHES FREE SURFACE.

(b) SINCE BOUNDARY VALUE IS THAT FREE SURFACE PRESSURE IS ZERO, A TENSION WAVE OF EQUAL AMPLITUDE REFLECTS. WITH DISTANCE FROM THE SURFACE, THE NET TENSION BUILDS UP TOWARDS THE FRACTURE STRESS.

(c) FRACTURE HAS OCCURRED, GENERATING A NEW FREE SURFACE. THE REMAINING COMPRESSION WAVE IS REFLECTING THERE.

FIGURE A-1

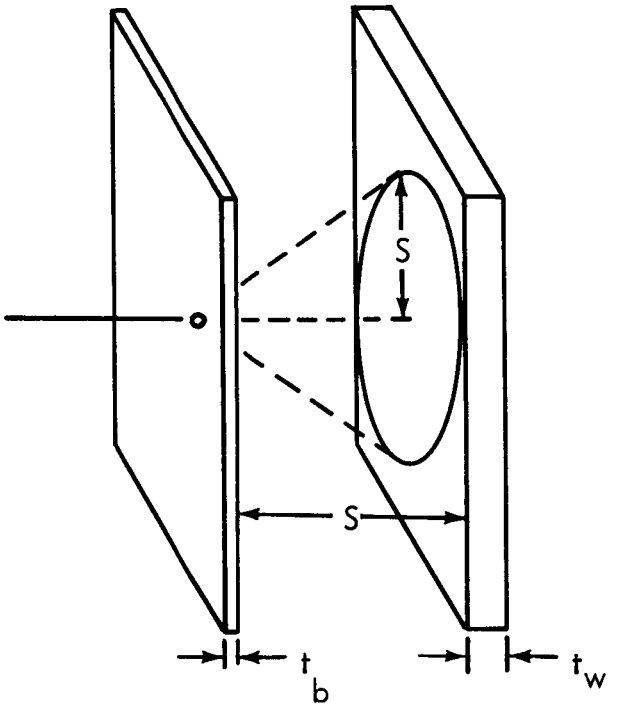


FIGURE A-2 BUMPER GEOMETRY

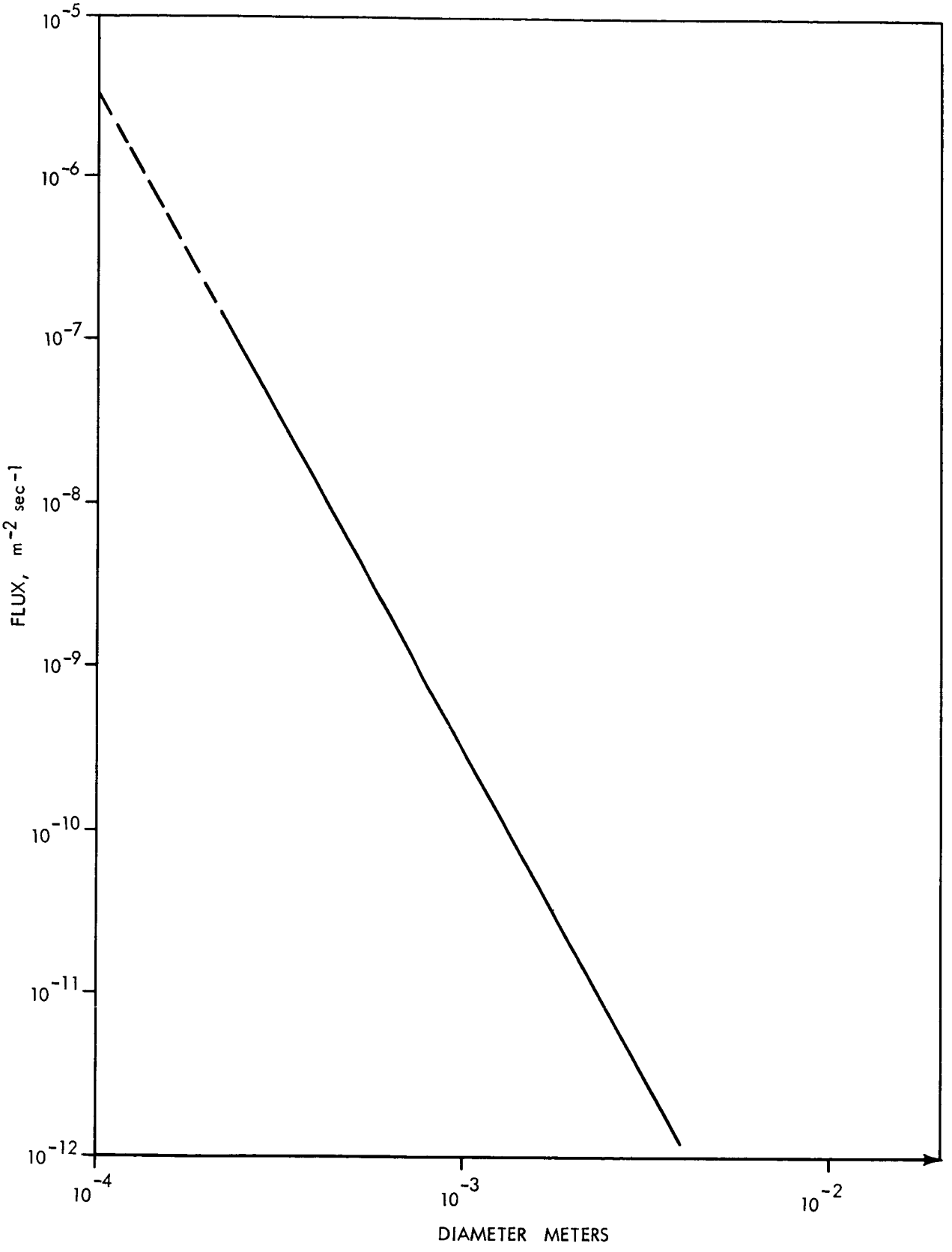


FIGURE B-1 MODEL METEOROID FLUX vs. DIAMETER

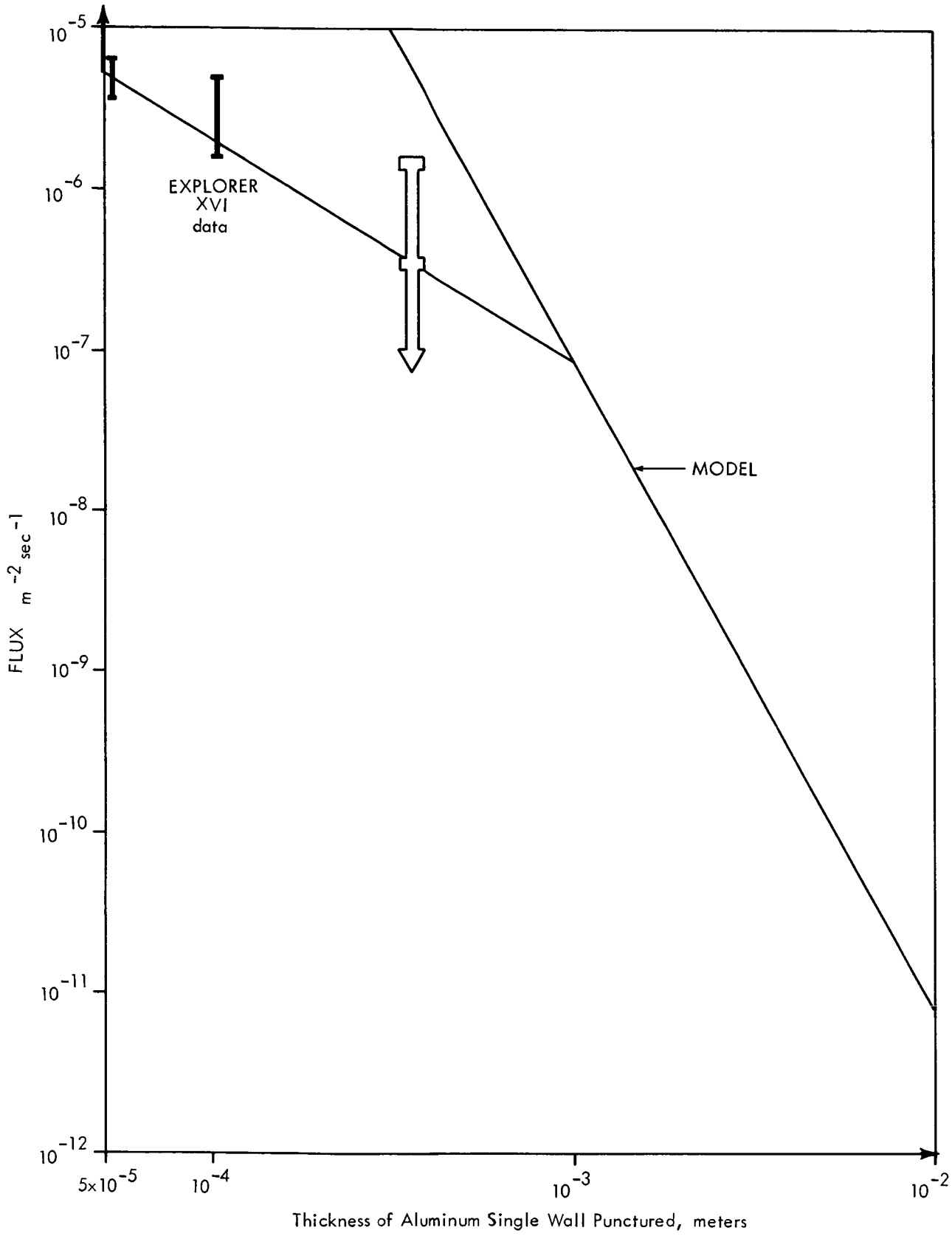


FIGURE B-2 PREDICTIONS OF MODEL AND EMPIRICAL RESULTS

DISTRIBUTION LIST

J. A. Hornbeck, Bellcomm
W. D. Lewis, Bellcomm
J. M. West, Bellcomm
T. H. Thompson, Bellcomm
W. S. Boyle, Bellcomm
W. A. Lee, NASA-MSC
O. E. Maynard, NASA-MSC
C. A. Perrine, NASA-MSC